

# The Discovery of a Second Luminous Low Mass X-ray Binary System in the Globular Cluster M15

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## ABSTRACT

Using the *Chandra* X-ray Observatory we have discovered a second bright X-ray source in the globular cluster M15 that is  $2.7''$  to the west of AC211, the previously known low mass X-ray binary (LMXB) in this system. Prior to the  $0.5''$  imaging capability of *Chandra* this second source could not have been resolved from AC211. The luminosity and spectrum of this new source, which we call M15-X2, are consistent with it also being a LMXB system. This is the first time that two LMXBs have been seen to be simultaneously active in a globular cluster. The new source, M15-X2, is coincident with a  $18^{\text{th}}$  U magnitude very blue star. The discovery of a second LMXB in M15 clears up a long standing puzzle where the X-ray and optical properties of AC211 appear consistent with the central source being hidden behind an accretion disk corona, and yet also showed a luminous X-ray burst suggesting the neutron star is directly visible. This discovery suggests instead that the X-ray burst did not come from AC211, but rather from the newly discovered X-ray source. We discuss the implications of this discovery for X-ray observations of globular clusters in nearby galaxies.

*Subject headings:* globular clusters: individual (M15) – Stars: individual (AC211) – X-rays: binaries – X-rays: individual (4U2127+119)

## 1. Introduction

The X-ray source 4U2127+119 associated with the globular cluster M15 was the first to be identified with an individual star within a cluster. The identification with the  $V \sim 15$  star AC211 was made by Auriere, le Fevre and Terzan (1984; AFT84) using the Einstein high resolution imager (HRI) position (Hertz and Grindlay 1983; HG83). The identification

was subsequently confirmed from a spectroscopic study by Charles, Jones and Naylor (1986), which showed characteristic signatures of a LMXB. AC211 has a modulation of 8.5 hr in the optical (Ilovaisky et al. 1987), which was subsequently seen in the X-ray band (Hertz 1987; H87), further strengthening the identification with AC211. Further observations and a more detailed analysis by Ilovaisky et al. (1993; I93) revealed the true orbital period to be 17.1. hr, twice the originally proposed value.

AC211 is optically one of the brightest of the known LMXB and yet has a relatively low X-ray luminosity of  $\sim 10^{36}$  ergs s $^{-1}$ . The high optical to X-ray luminosity ratio, suggests that a very luminous central X-ray source is hidden behind the accretion disk, with X-ray emission scattered into our line of sight via an extended accretion disk corona (AFT84, H87, Naylor et al. 1988). An extended X-ray emission region is also required to explain the smooth X-ray orbital modulation (H87, I93). This neat picture was put into doubt when a luminous X-ray burst from 4U2127+119 was recorded by the Ginga satellite (Dotani et al. 1990). This burst was long lived ( $> 150$  s) with a precursor event  $\sim 6$  s before the longer event. The peak luminosity of the burst was above  $10^{38}$  ergs s $^{-1}$ , with an expansion of the neutron star photosphere (Dotani et al. 1990; van Paradijs et al. 1990), meaning that the neutron star surface must have been directly observed. A dip in the continuum flux between the precursor and the main burst seemed to tie this event to the continuum X-ray source in M15. This result has been hard to reconcile with the idea that the central source in AC211 is hidden behind an accretion disk corona.

We report a *Chandra* High Energy Transmission Grating observation of the GC M15. The zero order grating image reveals two bright X-ray sources separated by  $\sim 2.7''$ , one associated with AC211 and the other a new source.

## 2. Results

4U 2127+119 was observed with the *Chandra* HETG grating in conjunction with the ACIS-S array on 2000 August 24, for a total exposure of order 21,000 s. The event file was gain corrected, using the calibration released on June 7 2001 (Caldb 2.6), screened for bad pixels and good time intervals. Streaks caused by the flaw in the serial readout of the chips were also removed. A histogram made on CCD grades shows that there is a large fraction of grade seven events, indicating considerable pile up. The zero order image from the cleaned event file using all grades is shown in Figure 1a and reveals the presence of two bright sources separated by  $2.7''$ . To determine the best source position we used data from all grades and determined the peak of the distribution in a box of  $3 \times 3$  pixels. The J2000 centroid positions of the two sources are M15-X1: R.A. (J2000) =  $21^h29^m58^s.25$ , Dec (J2000) =  $+12^\circ10'02''.9$  and M15-X2: R.A. (J2000) =  $21^h29^m58^s.06$ , Dec (J2000) =  $+12^\circ10'02''.6$ .

Accurate positions for AC211 were reported by Kulkarni et al. (1990) based on radio measurements and more recently by Geffert et al.(1994) based on meridian circle measurements and the PPM catalogue. The separation between the radio-meridian and radio-PPM positions range between  $0.2'' - 0.27''$ . Adopting the Kulkarni et al. (1990) position as a reference point for AC211, i.e. R.A.(J2000)= $21^h29^m58^s.31$ , Dec(J2000)= $+12^\circ10'02''.9$  then M15-X1 is within  $0.9''$  of AC211. This is consistent with the uncertainty in the *Chandra* attitude solution. To obtain the best coordinates for the second source we then corrected the image coordinates so as to give this position for AC211. This corresponded to a shift of  $0.94''$  in RA and  $0.03''$  in Dec of the reference coordinates and gives a revised position for the new source of R.A. (J2000)= $21^h29^m58^s.13$  and Dec (J2000)= $+12^\circ10'02''.6$ , with a very conservative uncertainty of  $0.5''$  taken from the size of 1 pixel in the *Chandra* detector. Following the *Chandra* new source naming convention we

designate the new source *CXO J212958.1+121002*. However, we will continue to refer to it here by the more memorable and concise name M15-X2.

To search for an optical counterpart we used the *Hubble Space Telescope* (HST) images published in Guhathakurta et al. (1996, kindly provided by Brian Yanni). The M15-X2 position is coincident with a faint very blue star. This can be seen in the HST color (U+B+V) image published in Guhathakurta et al. (1996). This star lies  $2.7''$  due west of AC211, and is  $< 0.13''$  from the *Chandra* position centroid. We have taken this color image and overlaid the  $0.5''$  *Chandra* error circle (Figure 1b). The very blue star corresponds to the star 590 in the De Marchi and Paresce (1994) list, who report that it has an equivalent U magnitude of 18.6. A blue optical counterpart is the classic signature of a LMXB (e.g. van Paradijs and McClintock 1996) and it seems likely this is the counterpart to the X-ray source.

The HEG and MEG orientation and dispersion direction, shown in Figure 1a relative to the position of AC211, are such that the dispersed grating spectra of the two sources are very close and overlapping. This effect is more severe in the HEG compare to the MEG. To extract the spectra of the two sources, histograms for the MEG and HEG along the cross-dispersion dimension (marked with TG\_D in Figure 1a) were fitted with Lorentzian models. The Lorentzian width was fixed at the value obtained from a similar histogram of a point source. The fitting results indicate that the two spectra are best separated in the MEG. The width of the HEG histogram is consistent with a single source, while the MEG requies a double Lorentzian fit (see Fig 2). We will concentrate on the MEG spectra because it is the least confused. The relative normalization between the two Lorentzians is  $\sim 2.5$ , with M15-X2 being the brighter source. This is consistent with the fact that most of the zero order grade seven events, caused by pile-up, are coincident with M15-X2. The MEG spectra were accumulated by selecting regions across the cross-dispersed direction, where

the contamination was a minimum. This is illustrated in Fig 2 where the two Lorentzian fits and the selected regions relative to the AC211 position are shown. The percentage of counts included in the extracted spectra is half for AC211 and about one fifth for M15-X2. The spectra of the two sources, separated by orders, were extracted with the *tgextract* routine included in Ciao 2.1. For each source the first order positive and negative MEG spectra were added together and grouped with a minimum of 20 counts per bin.

The fact that there are two bright LMXBs in M15 explains why the X-ray spectrum of what was previously thought to be a single source has in the past been found to be unusually complex (Sidoli, Parmar and Oosterbroek 2000; SPO00). The MEG spectra of the two sources are shown in Figure 3. The X-ray spectrum of AC211 is harder than that of M15-X2. The new source, M15-X2, can be fit with a single power law with an energy index of  $1.72 \pm 0.06$  and an absorption of  $< 3.4 \times 10^{20} \text{ H cm}^{-2}$ . Fixing the overall absorption at the expected value to M15 equivalent to a hydrogen column density of  $6.7 \times 10^{20} \text{ cm}^{-2}$  still gives an acceptable fit (reduced  $\chi^2$  of 1.14), with a power law index of  $1.89 \pm 0.05$ . In contrast, AC211 is not well fit by a single component power law or thermal bremsstrahlung model. A power law model gives a relatively hard photon index of 1.2 with an absorption of  $6 \times 10^{21} \text{ cm}^{-2}$ , but with a reduced  $\chi^2$  of 1.75. The partial covering model, one of several components used by SPO00 to fit the broader band BeppoSAX data (of the integrated spectrum of both sources), does provide an acceptable fit yielding a power law index of 2.1, a covering fraction of 0.87 with an absorption of  $2 \times 10^{22} \text{ cm}^{-2}$  and an overall absorption of  $1.6 \times 10^{21} \text{ cm}^{-2}$ . Fixing the absorption at the expected value for M15 gives a power law index of  $2.0 \pm 0.1$ , a covering fraction of  $0.92 \pm 0.01$  and an absorption of  $2.05 \pm 0.15 \times 10^{22} \text{ cm}^{-2}$ .

Using the expected point spread function for a single source we corrected for the partial extraction of the two sources. The 0.5–7.0 keV flux from AC211 is  $7 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}$ ,

corresponding to  $9 \times 10^{35}$  ergs s<sup>-1</sup> using a distance of 10.3 kpc to M15 (Harris 1996). For the new source, M15-X2 the 0.5-7.0 flux is  $1.1 \times 10^{-10}$  ergs cm<sup>-2</sup> s<sup>-1</sup>, corresponding to  $1.4 \times 10^{36}$  ergs s<sup>-1</sup>.

Light curves for the two sources were obtained extracting grating events from the same spectral regions selected along the cross-dispersion dimension. These are shown in Figure 4. AC211 is highly variable across the observation, typical of that reported in the past (see e.g. Illovaisky et al. 1987). Using the ephemeris given in I93 the observation began at orbital phase 0.2 and ended at 0.4, just prior to the predicted time of the partial eclipse. In contrast M15-X2 shows little variability, with just a very slight decline of a few percent across the observation.

We have examined the ROSAT HRI and Einstein HRI archival data for past evidence that the source was active. It is interesting to note that the original  $\pm 1''$  position from the Einstein HRI (HG83) lies closer to that of M15-X2, than AC211, and that the search for the optical counterpart by AFT84 was done using a circle of  $3.3''$ , the standard HRI 90% confidence error circle. The highest resolution archival images come from the ROSAT HRI and these show a marked elongation in the East-West direction, compared to the North-South – suggesting the M15-X2 source was present. The RXTE all sky monitor (ASM) light curve of M15 does not show any transient outburst around the time of the *Chandra* observation. The overall ASM light curve also supports the idea that the source is long lived and not transient. The ASM light curve is constant, except for short outbursts every  $\sim 365$  days. These outbursts occur when the source passes close to the sun, and are probably caused by sun glint on the detector collimator upsetting the solutions.

### 3. Discussion

This is the first time that two LMXBs have been seen to be simultaneously active in a globular cluster associated with our Galaxy. The separation of  $\sim 2.7''$  is less than the resolution of past X-ray telescopes. It is only with the superb  $0.5''$  quality imaging of the *Chandra* X-ray Observatory that what previously had been assumed to be just one source, is in fact two. The new X-ray source is 2.5 times brighter than AC211, and dominates the X-ray output of the M15 system. We identify the new source with a faint  $18^{\text{th}}$  U magnitude very blue star, that is characteristic of a LMXB and the most likely optical counterpart. It has a luminosity of  $\sim 10^{36}$  ergs s $^{-1}$  and power law X-ray spectrum with a photon index of  $\sim 1.75$ , both of which are typical of a LMXB X-ray burst source. The discovery of a second active LMXB in M15 brings a very simple solution to reconcile the schizophrenic properties of 4U2127+117, M5-X2 was the source of the burst detected by Ginga in 1988. <sup>2</sup>

The evidence that the central source in AC211 is hidden behind an accretion disk, with emission scattered into our line of sight by an accretion disk corona is now completely self consistent. The presence of a second source also resolves why the spectrum of 4U2127+119 was so complex (SPO00). The spectrum of AC211 is harder and bears a strong resemblance to that of the classic accretion disk corone source 4U1822-371 (White et al. 1981; White, Kallman and Angelini 1997). The luminosity of AC211 is now one third lower than previously thought. This both increases the amplitude of the orbital modulation and eclipse, and reduces the overall source luminosity – both strengthening the analogy with 4U1822-371 (White and Holt 1982).

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<sup>2</sup>Following this discovery we learned that Charles, van Zyl & Clarkson (2001 ; in preparation) have suggested that the strange properties of 4U2127+119 could be explained by a second source and were actively pursuing the confirmation of this proposal.



The ratio of LMXBs to stellar mass is more than two order of magnitudes higher for globular clusters than it is for the rest of the Galaxy (Clark 1975). This overabundance of LMXBs led Fabian, Pringle & Rees (1975) to propose that the LMXBs in globular clusters are formed via tidal capture of neutron stars in close encounters with main-sequence or giant stars, a mechanism that operates efficiently in the high stellar density found in globular clusters. Hut, Murphy and Verbunt (1991; HMOV91) discuss the probability of finding one or more LMXBs in any particular globular cluster. This depends strongly on how many neutron stars stay in the cluster after they are born and the lifetime of the LMXBs. In general these calculations suggest that more than one LMXB should be active in a globular cluster. The large number of millisecond radio pulsars found in globular clusters, thought to be the remains of LMXB systems, also points to many LMXBs having been active in the past (see HMOV91). To avoid the problem of there being so few LMXBs active in globular clusters it has been necessary to appeal to either short lifetimes (HMOV91) or larger fractions of neutron stars ejected from the globular cluster (Verbunt and Hut 1987). Given the small number of globular cluster systems with active LMXBs in our Galaxy, this discovery of two active LMXBs in M15 moves the observations in the right direction with respect to the theory and number of radio pulsars.

*Chandra* X-ray observations of nearby galaxies have identified many point X-ray sources with globular clusters (Sarazin, Irwin, & Bregman 2001, Angelini, Loewenstein, & Mushotzky 1991; ALM01). Many of these GC sources have luminosities above the Eddington limit for accretion onto a neutron star. ALM01 have suggested that these high luminosities may be due to multiple LMXBs being active in some GC systems. The discovery of two LMXBs active at the same time in M15 adds weight to that argument.

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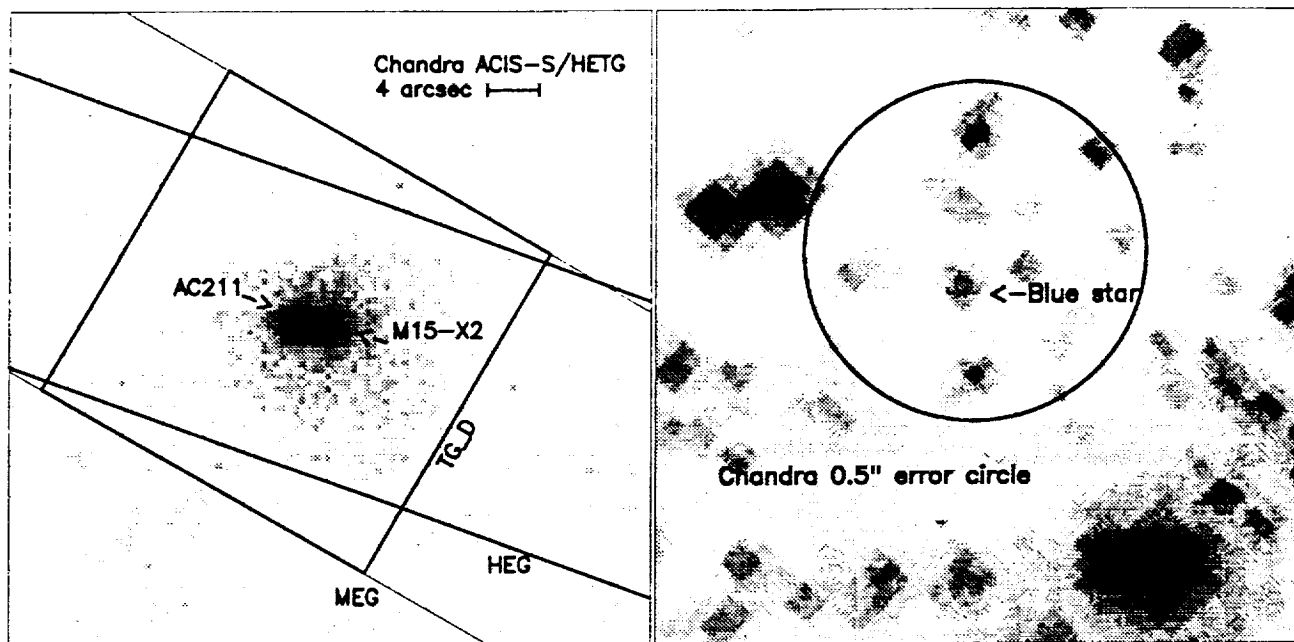


Fig. 1.— *Left* : The ACIS-S/HETG *Chandra* zero order image of M15 shows the location of the two sources. The tick lines across the image marks the orientation of the dispersion direction for the MEG and the HEG. They are separated by 10 degrees, with respect to AC211. The dispersion direction for the MEG and HEG to respect M15-X2 is offset by  $\sim 5$  pixels in the X direction and  $\sim 1$  pixel in the Y direction. The perpendicular line marked with TG.D (shown only for the MEG) indicates the cross-dispersion direction. The MEG count histogram (shown in Figure 2) is accumulated with respect to that dimension. *Right* : An enlargement of the U+B+V HST image taken from Guhathakurta et al. (1996) centered on the *Chandra* position of M15-X2. The star marked in the error circle is a blue star corresponding to star number 590 in De Marchi & Paresce (1994).

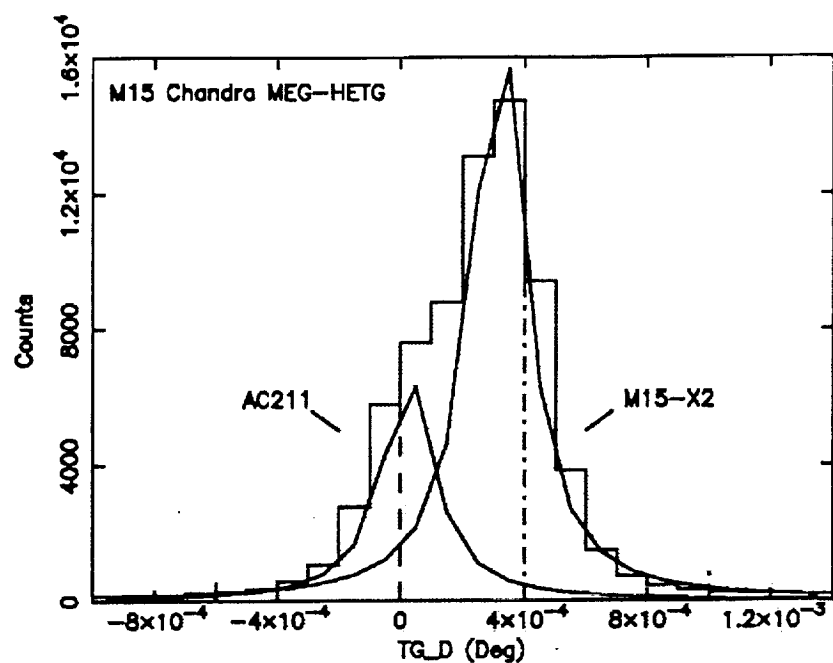


Fig. 2.— Histogram of the MEG cross-dispersion direction (TG.D) with respect to AC211, shown with the best Lorentzian fits to model the two sources. The dash and dash-dotted lines mark the regions selected to extract the spectra for AC211 and M15-X2. These are taken from the tail of the distribution to minimize contamination. The X-axis boundary of the M15-X2 region are shifted relative to the AC211 position to give an overall view from where the spectra were taken with respect to TG.D.

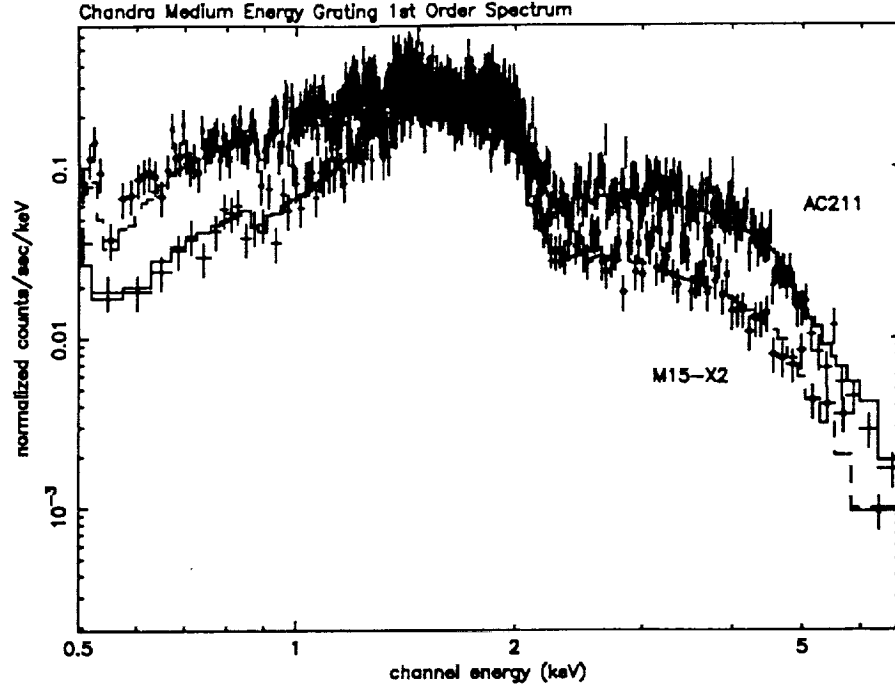


Fig. 3.— The MEG spectra for M15-X2 and AC211 with the best fit models shown as histograms.

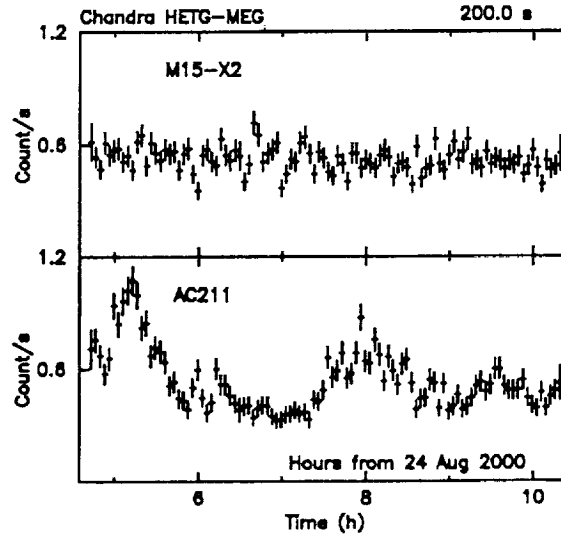


Fig. 4.— The 0.3-10 keV light curves of the two sources. The *Chandra* observation covers from phase 0.2 to 0.4 of the AC211 orbital period using the ephemeris published by I93.